Eur. Phys. J. C 29, 271–275 (2003)
Digital Object Identifier (DOI) 10.1140/epjc/s2003-01225-2

THE EUROPEAN
PHYSICAL JOURNAL C

Double meson production in ultraperipheral heavy-ion collisions

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Received: 20 March 2003 /
Published online: 2 June 2003 – © Springer-Verlag / Società Italiana di Fisica 2003

Abstract. The double-meson production in ultraperipheral heavy-ions collisions is addressed, focusing on the particular case of $\rho\, J/\Psi$ from two-photon reactions. The cross section at photon level is obtained using distinct parameterizations for the gluon distribution on the light meson. The resulting estimates for the nuclear case are presented and discussed. As a by-product, we estimate the double ρ production cross section using the pomeron-exchange factorization relations.

Relativistic heavy-ion collisions are a potentially prolific source of $\gamma\gamma$ collisions at high energy colliders [1,2]. The advantage of using heavy ions is that the cross sections vary as $Z^4\alpha^4$ rather than just as α^4 as in e^+e^- collisions. Moreover, the maximum $\gamma\gamma$ collision energy, $W_{\gamma\gamma}$, is $2\gamma/R_A$, about 6 GeV at RHIC and 200 GeV at LHC, where R_A is the nuclear radius and γ is the center-of-mass system (CMS) Lorentz factor of each ion. In particular, the LHC will have a significant energy and luminosity reaching beyond LEP2, and could be a bridge to $\gamma\gamma$ collisions at a future e^+e^- linear collider. For the large values of the energy at LHC the hard QCD pomeron is presumably the dominant mechanism of production. Consequently, the estimate of the cross sections should consider the QCD dynamics effects. Recently, we have proposed in [3,4] to investigate QCD pomeron effects in photon–photon scattering at ultraperipheral heavy-ion collisions. In particular, in [3] we have analyzed the diffractive double J/Ψ production in $\gamma\gamma$ collisions, with the photons coming from the Weizsäcker–Williams spectrum of the nuclei. For that process our results have indicated that future experimental analyses can be useful to discriminate the QCD dynamics at high energies. Here, we extend the analysis of double-meson production for the $\rho\, J/\Psi$ case using a perturbative approach and provide reliable estimates for the cross sections concerning that reaction. Since the pomeron-exchange factorization theorem [5,6] allows us to obtain the $\rho\rho$ cross section in terms of the $\rho\, J/\Psi$ and $J/\Psi\, J/\Psi$ cross sections, we use our results for these cross sections to estimate the double ρ production in ultraperipheral heavy-ion collisions. Moreover, since the double-meson production can also occur in photo-nucleus reactions if multiple interactions are considered, we compare our predictions for the two-photon process with that presented in [7] for the photonuclear case.

Let us start considering the $\rho\, J/\Psi$ production process at the photon level, that is $\gamma\gamma \to \rho\, J/\Psi$, with almost real photons. In the calculations presented here one follows the pioneering work in [8]. The goal of the present work is also twofold: to investigate a discrimination among models for the gluon distribution on the light meson in an enhanced nuclear cross section and to provide reliable estimates for the ultraperipheral nuclear cross section. The differential cross section is estimated in a similar way as the elastic J/Ψ photoproduction off the proton [9]. Therefore, it reads [8]

$$\begin{aligned}
&\frac{\mathrm{d}\sigma\,(\gamma\gamma \to \rho\, J/\Psi)}{\mathrm{d}t}\,(W_{\gamma\gamma}^2, t) \\
&= \mathcal{C}\,\alpha_{\mathrm{em}}\, g_\rho^2\, \frac{16\,\pi^3\,[\alpha_{\mathrm{s}}(M_{J/\Psi}^2/4)]^2\, \Gamma_{ee}^{J/\Psi}}{3\,\alpha_{\mathrm{em}}\, M_{J/\Psi}^5} \\
&\times \left[\, xG^\rho(x, M_{J/\Psi}^2/4)\,\right]^2 \exp\left(B_{\rho\, J/\Psi}\, t\right)\,, \qquad (1)
\end{aligned}$$

where $\mathcal{C}$ denotes factors of corrections discussed later on. The two-photon CMS energy is denoted by $W_{\gamma\gamma}$, where $x = M_{J/\Psi}^2/W_{\gamma\gamma}^2$ and $M_{J/\Psi}$ is the heavy-meson mass. In the small-t approximation, the slope is estimated to be $B_{\rho\, J/\Psi} = 5.5 \pm 1.0\,\mathrm{GeV}^{-2}$ (see further discussion below and [8]). The light meson–photon coupling is denoted by $g_\rho^2 = 0.454$ and the heavy-meson decay width into a lepton pair is Γ_{ee}.

The process above was proposed as a probe of the gluon distribution on the meson xG^ρ and, as a consequence, a constraint for the photon structure. The enhancement in the sensitivity by taking the square of those distributions in the total cross section could discriminate them in measurements at the future photon colliders. In Fig. 1, we present the distributions for the parameterizations considered here as a function of the two-photon

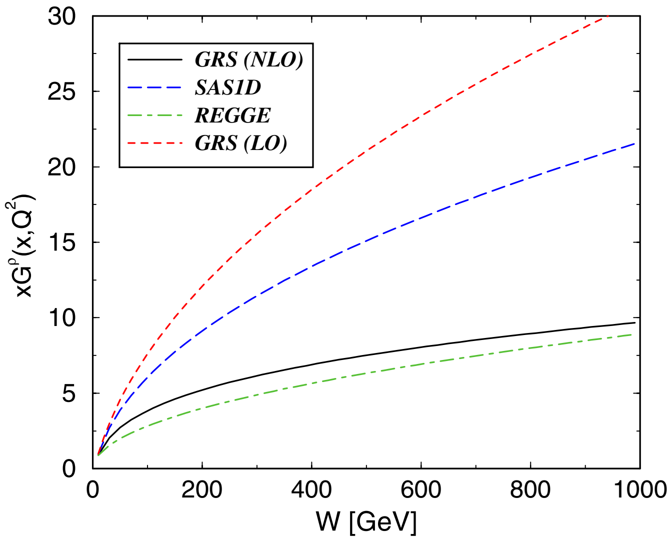

Fig. 1. The gluon distribution on the light meson for different parameterizations. The solid and dashed lines are NLO and LO GRS, respectively. The long-dashed line denotes the SaS1D parameterization and the dot-dashed one the Regge motivated ansatz

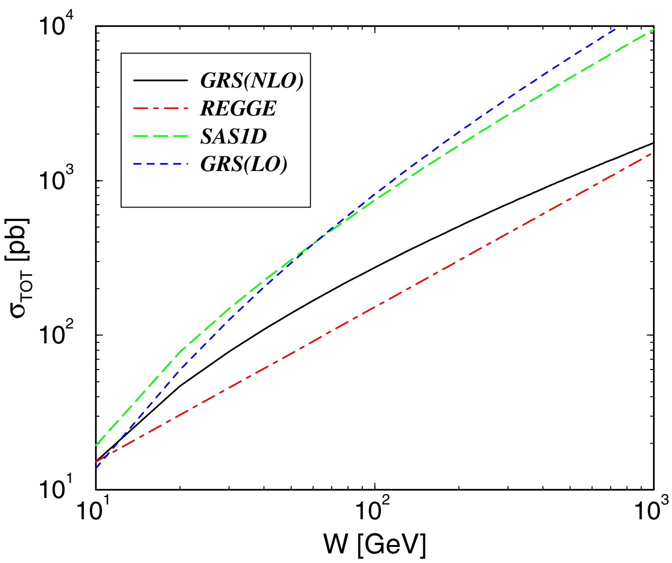

Fig. 2. The total cross section for the process $\gamma\gamma \to \rho\, J/\Psi$ as a function of the two-photon CMS energy. The distinct curves correspond to the different parameterizations

CMS energy. These are the following: the LO (dashed line) and NLO (solid line) GRS [10] parameterization; the SaS1D parameterization [11] (long-dashed line) and the phenomenological Regge motivated ansatz (dot-dashed line) proposed at [8]. The latter is given by

$$x\, G^\rho(x, M^2_{J/\Psi}/4) = x_0\, G^\rho(x_0, M^2_{J/\Psi}/4) \left(\frac{x_0}{x}\right)^{\omega_{I\!P}-1}, \quad (2)$$

with $x_0 = 0.1$ and the pomeron intercept is considered to be $\omega_{I\!P} = 1.25$, in agreement with the effective power in the HERA data. In the further analysis for the nuclear case we allow for a higher intercept, in order to simulate a BFKL-like behavior, motivated by the studies in the double J/Ψ production [3]. The normalization, $x_0\, G^\rho(x_0, M^2_{J/\Psi}/4)$, is given by the NLO-GRS parameterization. The differences among the parameterizations are sizeable as a consequence of the distinct effective exponent λ. The GRS LO one presents the steeper behavior, followed by SaS1D ($\lambda = 0.3038$). The Regge motivated and GRS NLO parameterizations are closer, since the intercept for the Regge ansatz is similar to the effective power of GRS NLO ($\lambda \simeq 0.228$). These behaviors will produce distinct results for the total cross section at the photon level and in the nuclear case, allowing one to make a discrimination in future colliders.

Let us now calculate the total cross section at photon level considering the models for the gluon distribution on the light meson referred to above. In order to do so, we address the correction factor $\mathcal{C}$. It accounts for several improvements to the process like the partons' skewness (off-diagonal) [12], QCD NLO corrections to the $\gamma\, J/\Psi$ impact factor [13] and the real part of the amplitude. Following [8], one has $\mathcal{C} = C_{\rm off}\, C_{\rm NLO}\, C_{\rm rp}$, where the correction factors are taken as

$$C_{\rm off} \simeq 1.2\,, \qquad C_{\rm NLO} \simeq 1 + \frac{\alpha_{\rm s}\,(M^2_{J/\Psi}/4)}{2}\,, \quad (3)$$

$$C_{\rm rp} \simeq 1 + \frac{\pi^2\,\lambda}{4}\,, \qquad \lambda = \frac{\partial \log\,[\,xG(x,Q^2)\,]}{\partial \log(1/x)}\,. \quad (4)$$

In Fig. 2 we show our predictions for the total cross section $\sigma_{\rm tot}(\gamma\gamma \to \rho\, J/\Psi)$ as a function of the two-photon CMS energy, extrapolated up to 1 TeV. The behavior on the energy of the total cross section is strongly dependent on the choice of the gluon content of the light meson. In particular, a strong enhancement of the cross section is predicted if we assume the LO GRS parameterization, $C_{\rm NLO} = 1$ and disregard the real part of amplitude. The other predictions are similar to the results obtained in [8]. It is worth mentioning that this process has also been calculated in [14], considering a two-pomeron model supplemented by the dipole–dipole picture. There, the result is similar to the Regge ansatz and lower than the other parameterizations considered here.

Recently, the FELIX Collaboration has proposed the construction of a full acceptance detector for the LHC, with a primary proposal providing comprehensive observation of a very broad range of strong-interaction processes. In particular, studies of two-photon physics in AA collisions have been discussed in its proposal [15]. There, the differential cross section $\mathrm{d}\sigma(\gamma\gamma \to V_1V_2)/\mathrm{d}t$, with $V_i = \rho, J/\Psi$ ..., was parameterized in the form

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t}(\gamma\gamma \to V_1V_2) \quad (5)$$
$$= A_{V_1V_2} \left(\frac{W}{W_0}\right)^{C_{V_1V_2}} \exp\left(t\, B_{V_1V_2} + 4\, t\alpha'_{V_1V_2} \ln \frac{W}{W_0}\right),$$

where $A_{V_1V_2} = 1.1\,\mathrm{nb/GeV^{-2}}$, $B_{V_1V_2} = 2.5\,\mathrm{GeV^{-2}}$, $C_{V_1V_2} = 0.8$ and $\alpha'_{V_1V_2} = 0$ for the $\rho\, J/\Psi$ case. In Fig. 3 we compare the FELIX prediction (long-dashed line) with our results obtained considering the Regge motivated and GRS

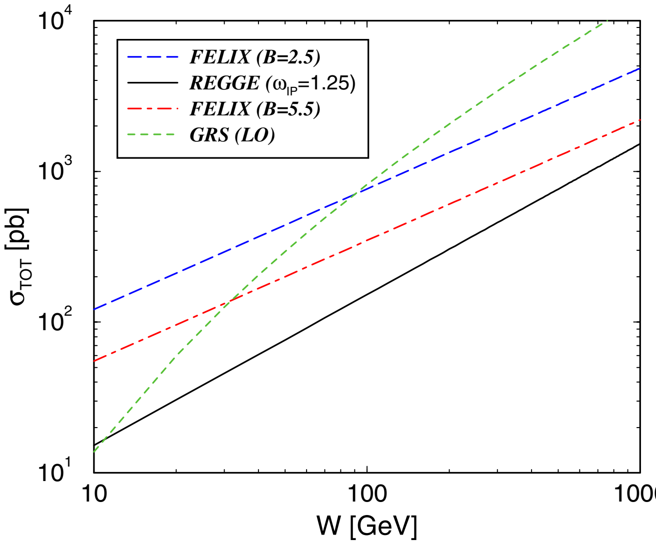

Fig. 3. The same as Fig. 2 considering the FELIX ansatz for the cross section and different values of the slope. For comparison our predictions using the Regge motivated input is also presented

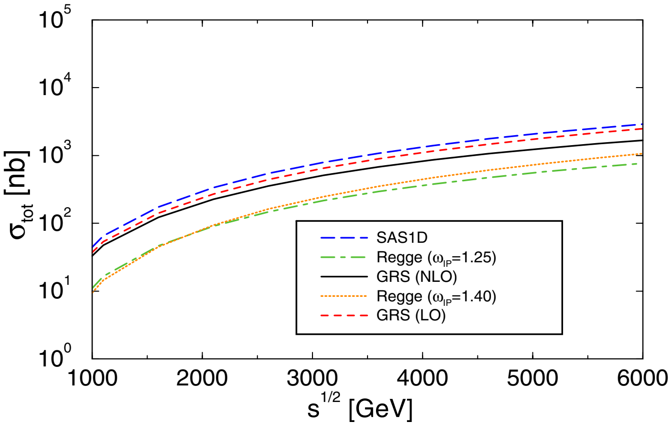

Fig. 4. The total cross section for $\rho\, J/\Psi$ production in two-photon ultraperipheral heavy-ion collisions as a function of the ion CMS energy $\sqrt{s}$ ($A = 208$). The distinct curves correspond to the different parameterizations

(LO) gluon parameterizations as input. Moreover, since in this paper we are considering $B_{\rho\, J/\Psi} = 5.5\,\mathrm{GeV}^{-2}$, we also present the FELIX prediction for the cross section if we assume this value for the slope. We see that there is a reasonable agreement between the distinct predictions for the cross section at the photon level. Our conclusion at this level is that the forthcoming photon colliders could experimentally check our predictions, which will shed light on the vector meson and photon structure.

One comment is in order here. Our value for the slope is corroborated by the recent results for ρ and J/Ψ production at HERA and the proof of the factorization hypothesis for the slope parameters [6], which predicts that

$$B_{\gamma\gamma\to\rho\, J/\Psi}(W) = \frac{B_{\gamma p\to\rho p}(W) \times B_{\gamma p\to J/\Psi p}(W)}{B_{pp}(W)}\,, \quad (6)$$

where $B_{\gamma p\to\rho p}$, $B_{\gamma\gamma\to J/\Psi p}$ and B_{pp} are the slope of the diffractive peak for the reactions $\gamma p \to \rho p$, $\gamma p \to J/\Psi p$ and $pp \to pp$, respectively. Data on $\gamma p \to Vp$ in the energy range $50\,\mathrm{GeV} < W < 100\,\mathrm{GeV}$ give $B_{\gamma p\to\rho p} \approx 11\,\mathrm{GeV}^{-2}$ and $B_{\gamma p\to J/\Psi p} \approx 5\,\mathrm{GeV}^{-2}$. From pp reactions one obtains $B_{pp} = 10$–$12\,\mathrm{GeV}^{-2}$. Consequently, assuming the validity of the factorization we find that $B_{\gamma\gamma\to\rho\, J/\Psi} \approx 5.5\,\mathrm{GeV}^{-2}$ is predicted, which is in agreement with the ansatz proposed in [8].

We are now ready to compute the double-meson production in ultraperipheral heavy-ions collisions. For two-photon reactions, the cross section for the process $AA \to AA\rho\, J/\Psi$ will be written as

$$\sigma_{AA\to AA\rho\, J/\Psi}(s) = \int \mathrm{d}\tau\, \frac{\mathrm{d}\mathcal{L}_{\gamma\gamma}}{\mathrm{d}\tau}\,(\tau)\, \hat{\sigma}_{\gamma\gamma\to\rho\, J/\Psi}\,(\hat{s}), \quad (7)$$

where $\tau = \hat{s}/s$, $\hat{s} = W^2_{\gamma\gamma}$ is the square of the CMS energy of the two photons and s of the ion–ion system, $\frac{\mathrm{d}\,\mathcal{L}_{\gamma\gamma}\,(\tau)}{\mathrm{d}\tau}$ is the two-photon luminosity and $\hat{\sigma}_{\gamma\gamma\to\rho\, J/\Psi}(\hat{s})$ is the cross section of the $\gamma\gamma$ interaction. (For details related to the numerical expressions for the effective photon luminosity, see [3].) Our approach excludes possible final state interactions of the produced particles with the colliding particles, allowing reliable calculations to be made of ultraperipheral heavy-ion collisions.

In Fig. 4 are presented the results for the distinct parameterizations discussed above, considering $A = \mathrm{Pb}$. For the sake of completeness, we also include the Regge ansatz with a higher pomeron intercept, $\omega_{I\!P} = 1.4$, along the lines of the studies on double J/Ψ production [3]. An upper bound is given by the SaS1D parameterization and the lower one by the Regge ansatz with the lower pomeron intercept $\omega_{I\!P} = 1.25$. At the LHC energies $\sqrt{s} = 5500\,\mathrm{GeV}$, the cross section takes values between 680 nb and 2.6 mb, showing that the process can be used to discriminate among parameterizations. It should be noted that the ultraperipheral cross section is dominated by not so high two-photon energies. Although the deviations among the models are quite sizeable at very high energies, as shown in Fig. 2, in the nuclear cross section such deviations are less sizeable. This is directly related to the effective two-photon luminosity, which peaks at smaller $W_{\gamma\gamma}$. Therefore, correct estimates should include a careful treatment of the low energy threshold effects. The nuclear cross section is enhanced in relation to the e^+e^- case, which provides values of hundreds of pb in contrast with the units of mb in the peripheral nuclear case.

In Fig. 5 the results considering the FELIX ansatz for the two-photon cross section and different values of the slope are presented. For comparison the predictions obtained with our approach and the GRS (LO) input are also shown. We see that the large difference between the GRS (LO) and FELIX results for low energies in the two-photon case (see Fig. 3) implies that the values predicted by the FELIX Collaboration are ever larger than obtained using our approach, independently of the value of slope used. As a cross check, we also present in Fig. 5 the pre-

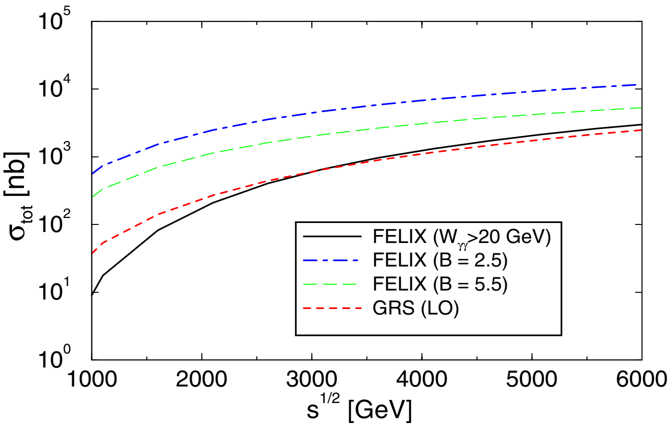

Fig. 5. The same as Fig. 4 considering the FELIX ansatz for the cross section with (solid curve) and without (dot-dashed curve) the kinematical cut. For comparison our prediction using GRS (LO) input is also presented

dictions for $\rho\, J/\Psi$ production in ultraperipheral heavy-ion collisions obtained using the FELIX ansatz and the kinematical cut proposed in [15]. We see that our results agree with those presented in that reference.

As a by-product we can use our results for double J/Ψ production obtained in [3] and that presented above for $\rho\, J/\Psi$ production to estimate the double ρ production in ultraperipheral heavy-ion collisions, using the factorization theorem to relate the distinct cross sections. Given the assumption that single-pomeron exchange dominates, the following relation among the distinct differential cross sections is predicted:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t}(\gamma\gamma \to V_1 V_1) = \frac{\left[\frac{\mathrm{d}\sigma}{\mathrm{d}t}(\gamma\gamma \to V_1 V_2)\right]^2}{\frac{\mathrm{d}\sigma}{\mathrm{d}t}(\gamma\gamma \to V_2 V_2)} . \quad (8)$$

The usual approximation in the small t region, $\mathrm{d}\sigma/\mathrm{d}t = A\exp(Bt)$, where $A = (\mathrm{d}\sigma/\mathrm{d}t)_{t=0}$, gives

$$\sigma(\gamma\gamma \to \rho\rho) = \frac{(B_{\rho\, J/\Psi})^2}{B_{\rho\rho} \times B_{J/\Psi\, J/\Psi}} \times \frac{[\sigma(\gamma\gamma \to \rho\, J/\Psi)]^2}{\sigma(\gamma\gamma \to J/\Psi\, J/\Psi)} . \quad (9)$$

The slope of the diffractive peak for the $\gamma\gamma \to J/\Psi\, J/\Psi$ process was estimated in [3] to be $B_{J/\Psi\, J/\Psi} = 1/m_c^2$, where m_c is the charm quark mass. Using the factorization theorem for the slopes, similarly to the use that was made of it in (6), we estimate $B_{\rho\rho} \approx 12.1\,\mathrm{GeV}^{-2}$. In Tables 1 and 2 we present our predictions for the double ρ production in $\gamma\gamma$ and ultraperipheral AA collisions, considering different scenarios for the QCD dynamics. We can see that there is a large range of possible values for the cross section, which implies that future experimental data are essential to constrain the dynamics. It is important to stress that our predictions agree with those presented in [15].

In [7] it was emphasized that due to the large cross sections for vector meson production in photon–pomeron interactions, the probability of having multiple interactions in a single nucleus–nucleus encounter is non-negligible. Therefore, it is possible that in double photonuclear interactions occur the production of two mesons, generating a similar signal of the two-photon processes discussed here. There, the authors have presented some estimates of the cross sections for the production of vector mesons pairs in lead beams at LHC neglecting possible correlations between the multiple interactions (See Table V of [7]). Consequently, it is important to compare the predictions for the production of meson pairs in two-photon and photon–pomeron interactions. Our predictions indicate that $\sigma(AA \to AA\rho\, J/\Psi) \leq 10\,\mu\mathrm{b}$ and $\sigma(AA \to AA\rho\rho) \leq 1250\,\mu\mathrm{b}$, independently of the scenario considered. These values are almost one order of magnitude below the predictions presented in [7], which implies that the rates of photonuclear multiple interactions would be an important background for the two-photon reactions, and also for double-meson production. In principle, an analysis of the impact parameter dependence should allow one to distinguish between the two classes of reactions, since two-photon interactions can occur at a significant distance from both nuclei, while a photonuclear interaction must occur inside or very near a nucleus. We stress the salient point that the experimental separation between the two classes of processes is important; this deserves more studies.

Table 1. The double ρ production cross sections in $\gamma\gamma$ processes ($W = 100\,\mathrm{GeV}$). The notation BFKL (LO/MOD) corresponds to the treatment for the double J/Ψ production in [3] and GRS (LO/NLO), Regge, correspond to the treatment for the $\rho\, J/\Psi$ production presented here

Scenario	$\sigma(\gamma\gamma \to \rho\rho)$ (pb)
BFKL (LO) + GRS (LO)	5×10^3
BFKL (LO) + GRS (NLO)	800
BFKL (LO) + Regge ($\omega_{I\!P} = 1.25$)	50
BFKL (MOD) + GRS (LO)	5×10^5
BFKL (MOD) + GRS (NLO)	80×10^3
BFKL (MOD) + Regge ($\omega_{I\!P} = 1.25$)	5×10^3

Table 2. The double ρ production cross sections in ultraperipheral heavy-ion collisions at LHC ($\sqrt{s} = 5500\,\mathrm{GeV}$) for PbPb. Same notation as in the previous table

Scenario	$\sigma(AA \to AA\rho\rho)$ (nb)
BFKL (LO) + GRS (LO)	25×10^3
BFKL (LO) + GRS (NLO)	4×10^3
BFKL (LO) + Regge ($\omega_{I\!P} = 1.25$)	810
BFKL (MOD) + GRS (LO)	125×10^4
BFKL (MOD) + GRS (NLO)	20×10^4
BFKL (MOD) + Regge ($\omega_{I\!P} = 1.25$)	405×10^2

As a summary, in this paper we have estimated the $\rho\, J/\Psi$ and $\rho\rho$ production in two-photon processes at ultraperipheral heavy-ion collisions. We have verified that if these measurements are feasible, a discrimination among the current parameterizations for the gluonic content of the mesons is possible. As a consequence, the analysis allows one to constrain the partonic content to the photon structure function. Using the pomeron-exchange factorization relations, the rates for double-meson production were calculated and contrasted with the current predictions in the literature. The values found are in agreement with previous estimates. Concerning possible background processes, it was verified that the multiple meson production in photonuclear reactions constitutes the main source. The experimental separation between such processes should be taken into account, in particular focusing on the impact parameter dependence and on the rapidity distribution.

Acknowledgements. This work was partially financed by the Brazilian funding agencies CNPq and FAPERGS. M.V.T.M. thanks the support of the High Energy Physics Phenomenology Group at the Institute of Physics, GFPAE IF-UFRGS, Porto Alegre.

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